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GAMMA AND NEUTRON DOSE MEASUREMENTS FOR A THERMAL TUNGSTEN NUCLEAR ROCKET CRITICAL EXPERIMENT

by

G. Houghton

C. Jupiter

G. Trimble

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract SNPC-27

GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

JOHN JAY HOPKINS LABORATORY FOR PURE AND APPLIED SCIENCE

P.O. BOX 608, SAN DIEGO, CALIFORNIA 92112

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Technical Management
NASA-Lewis Research Center
Cleveland, Ohio
Nuclear Systems Division
D. Bogart

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I. INTRODUCTION

This report describes the measurement of the gamma and neutron dose distributions in Core III of the Thermal Tungsten Nuclear Rocket Critical Experiment.[1, 2] The reactor core consisted of a cylindrical array of fuel elements and poison tubes in a water filled tank as shown in Fig. 1. A top view of the core shown in Fig. 2 illustrates the twelve-fold symmetry of the core assembly, the large circles representing fuel elements and the smaller ones representing cadmium nitrate filled poison tubes. Radial and axial dose distributions in the core were measured by inserting specially constructed thimble ionization chambers in the hollow spine of the fuel elements and in the poison tubes. The dosimeters were of two types; one sensitive mainly to energy deposition from gamma rays and fast neutrons. The absolute gamma sensitivity of the ionization chambers was determined using an X-ray machine, Co^{60} radiation and 7 MeV electron bremsstrahlung. The radiative energy deposition in the neutron dosimeters was determined by comparing the dosimeter response with that of a water calorimeter in a TRIGA Mark I reactor. A time history of the gamma intensity in the critical assembly core was also measured, showing the contribution of delayed gamma to the total gamma radiation.

II. THIMBLE IONIZATION CHAMBERS

The two types of thimble ionization chambers used for these measurements were: a) carbon walled, carbon dioxide filled chambers for gamma dosimetry and b) polyethylene walled, ethylene gas filled chambers for fast neutron dosimetry. The configuration of the radiation-sensitive portion of the chambers were designed at General Atomic; the chambers were fabricated by the Landsverk Electrometer Company and incorporated into the standard Landsverk charging system. The chambers are shown diagrammatically in Figs. 3 and 4. An exploded view of one of these is shown in Fig. 5. The chambers were hermetically sealed so that

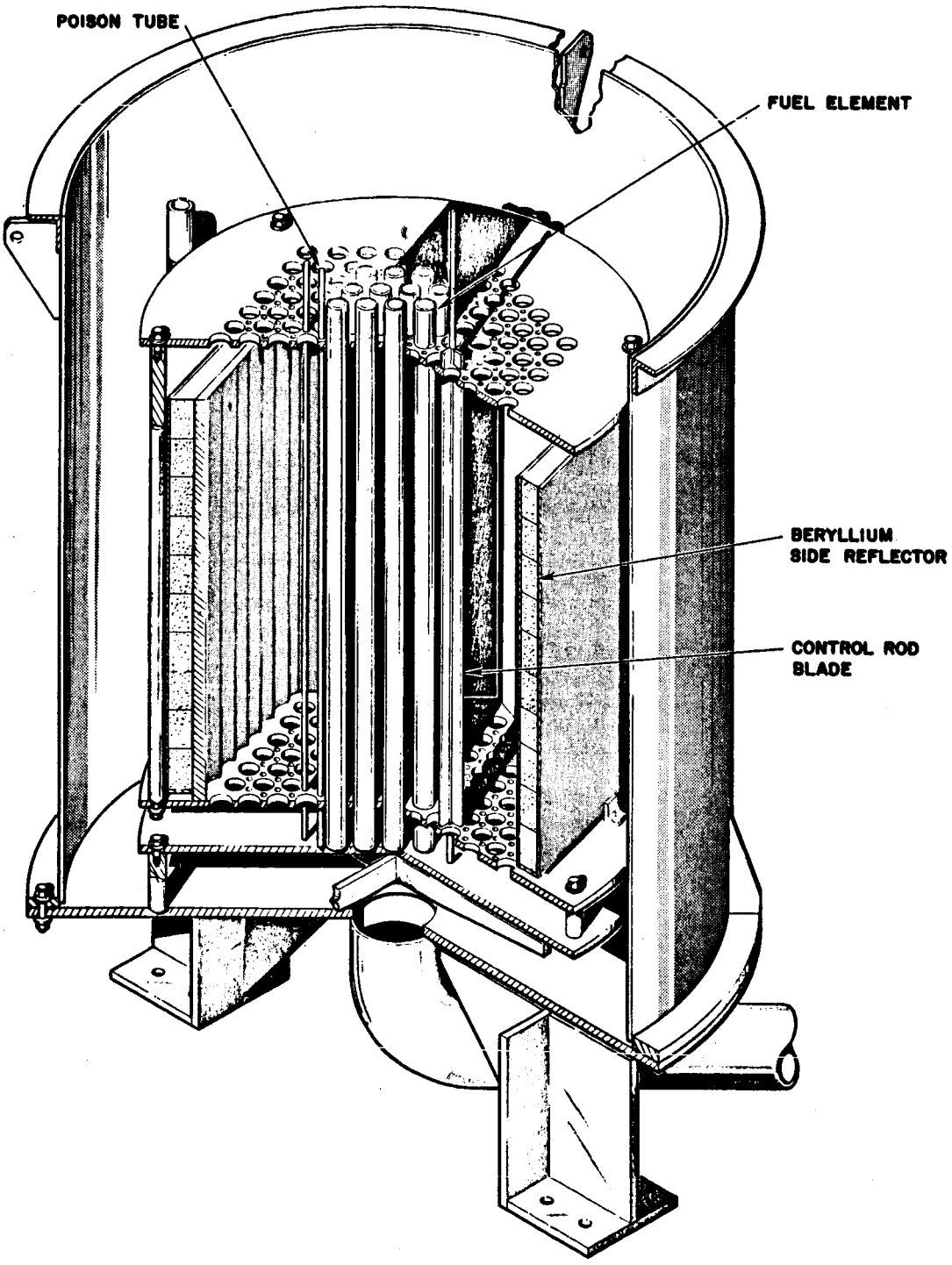


Fig. 1--Cross section of reactor tank and core support structure

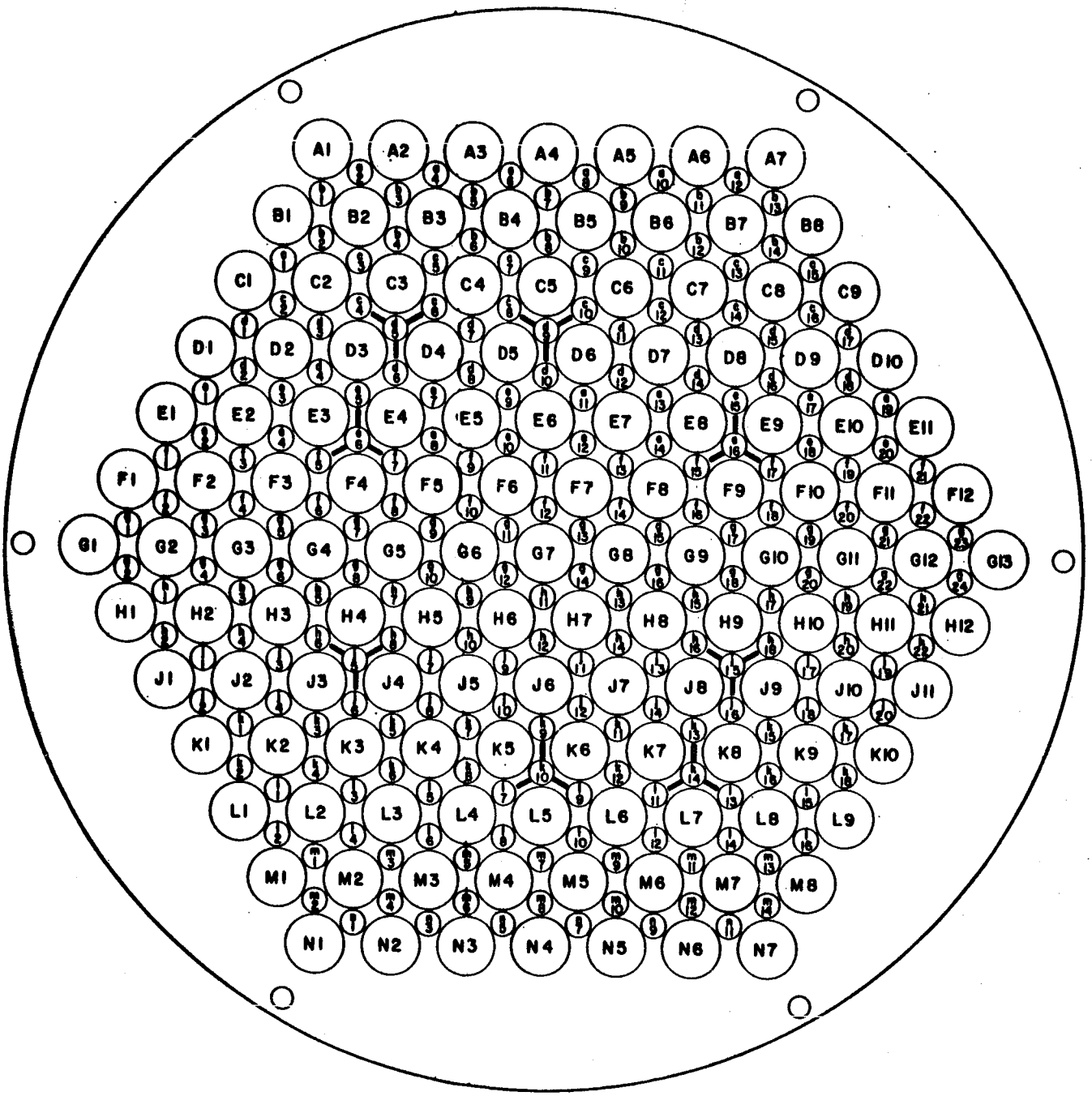
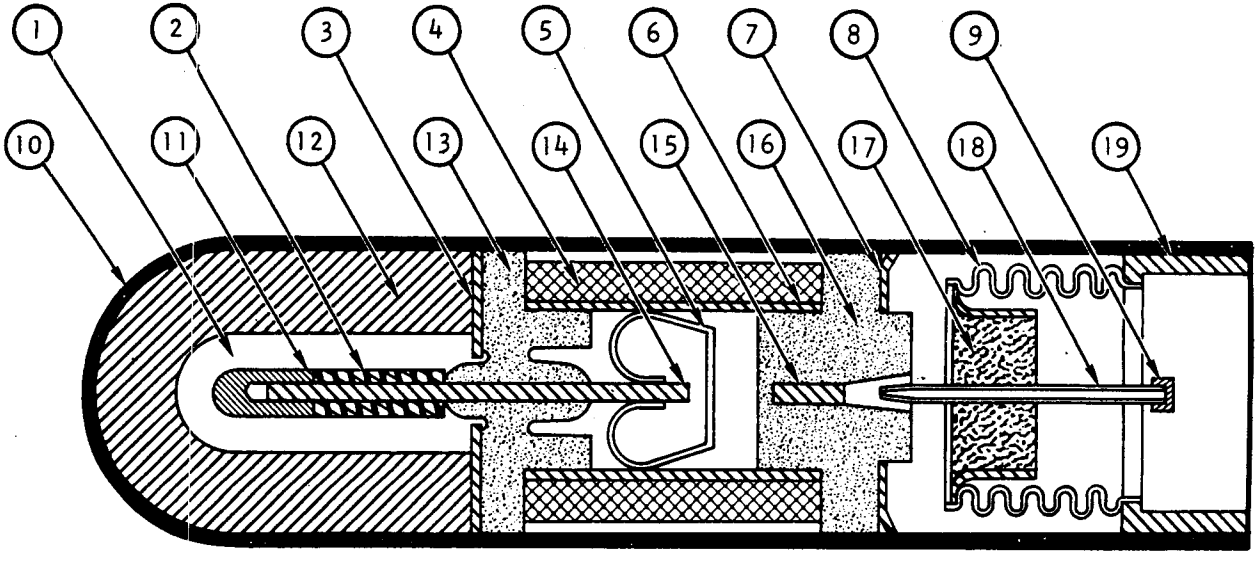
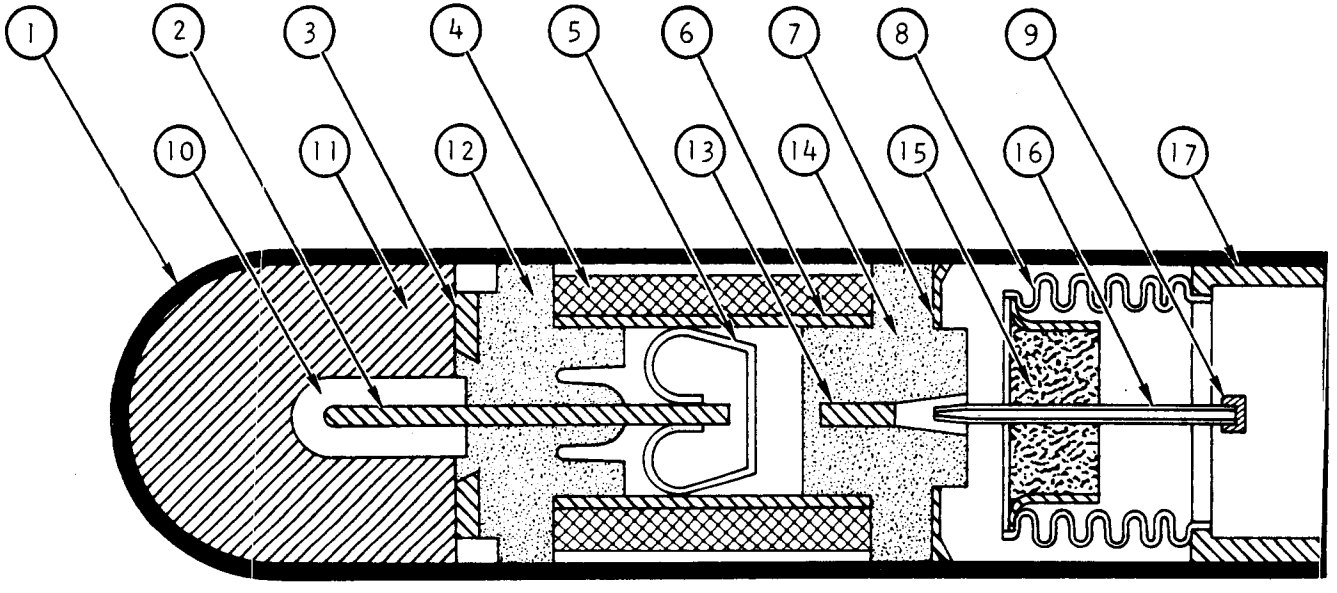


Fig. 2--Gridplate identification scheme



1. IONIZABLE VOLUME - 0.176 CU. CM. (CARBON DIOXIDE GAS)
2. CARBON ELECTRODE SHEATH (0.064 IN. DIA.)
3. ALUMINUM SHIELD (0.015 IN. THICK)
4. CONDENSER (6000 MMFD.)
5. ELECTRODE CLIP
6. ALUMINUM CONDENSER CORE
7. RETAINER RING
8. BELLOWS ASSEMBLY
9. END CAP
10. ALUMINUM SHELL 1.900 IN. LONG - 490 IN. DIA. - 0.015 IN. WALL
11. ALUMINUM ELECTRODE CAP
12. CARBON CHAMBER (0.134 IN. WALL)
13. ELECTRODE INSULATOR
14. ALUMINUM ELECTRODE
15. ELECTRODE CONTACT BAR
16. CONDENSER INSULATOR
17. GLASS SEAL
18. CONTACT PIN
19. END SLEEVE

Fig. 3--Carbon dosimeter details (2500 rad)



1. ALUMINUM SHELL
   1.850 IN. LONG - 0.490 IN. DIA.
   - 0.015 IN. WALL
2. ALUMINUM ELECTRODE (0.025 IN. DIA.)
3. BAKELITE SHIELD
4. CONDENSER (3000 MMFD.)
5. ELECTRODE CLIP
6. ALUMINUM CONDENSER CORE
7. RETAINER RING
8. BELLOWS ASSEMBLY
9. END CAP
10. IONIZABLE VOLUME 0.040 CU. CM.
    (ETHYELENE GAS)
11. POLYETHELYENE CHAMBER
    (0.165 IN. WALL)
12. ELECTRODE INSULATOR
13. ELECTRODE CONTACT BAR
14. CONDENSER INSULATOR
15. GLASS SEAL
16. CONTACT PIN
17. END SLEEVE

Fig. 4--Polyethylene dosimeter details (5000 rad)

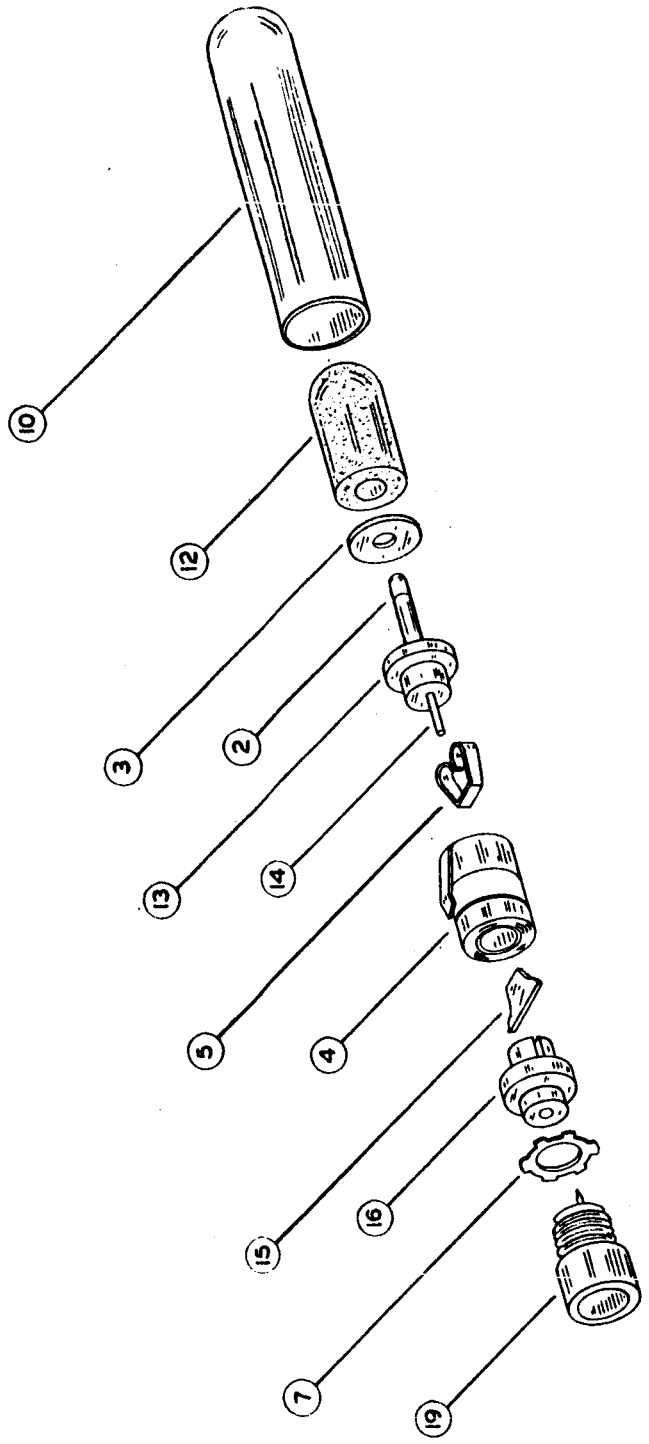


Fig. 5--Disassembly view of carbon dosimeter

they could be immersed in water without discharging them. They were charged and read by exerting pressure on the contact pin; this stretches the bellows until the pin makes contact with the electrode (see Fig. 3).

The charger-reader was a Landsverk Model L-64 which has a small capacitance compared to that of the ionization chambers and therefore can be ignored. The electrical leakage rate of the dosimeters was about 2% full scale per day.

The design of the thimble ionization chambers is discussed in the following two sections.

2.1 GRAPHITE-CARBON DIOXIDE THIMBLE IONIZATION CHAMBERS

Sixteen chambers having graphite walls, filled with carbon dioxide, and sensitive primarily to energy deposition from gamma rays were used. These devices have a small inherent neutron sensitivity due to carbon recoils. Because of the short range of the recoils, virtually all of the neutron response results from ionization created by particles originating in the gas. In order to reduce the response to ionization produced in the cavity by proton recoils from the polystyrene insulator the chambers were designed so that only a small solid angle was subtended by the effective cavity volume at the insulator. This is the purpose of the 0.015-in. thick aluminum shield shown in Fig. 3. The effectiveness of this design is aided by the poor collection efficiency near the insulator. The outside diameter of the chambers was limited to 0.490 in. so that they would fit into the center of the fuel element support post and the poison tubes. This limited the thickness of the graphite walls to 0.544 gm/cm^2 which exceeds the range of a 1.25 MeV electron and provide for charged particle equilibrium[3, 4] for a 1.5 MeV photon. During the measurements the ionization chambers were surrounded by aluminum in the fuel elements and both aluminum and water in the poison tubes; this in effect increased the thickness of wall material surrounding the ionizable volume of the

chambers. Generally, equilibrium ionization is reached at thicknesses much less than the range of the highest energy secondary electron. Assuming that only aluminum surrounded the ionizable volume, then for Compton interactions the absorbed dose would be 4% less than for carbon. If the ionizable volume is surrounded by water, the absorbed dose would be 11% more.[4] Since the carbon walls are an equilibrium thickness for 1.50 MeV gammas, only those gammas above this range are in question. However, in the worst case, i.e., assuming water around the carbon wall dosimeter, and considering that only about 0.4 of the fission energy is above this value, the error caused by the walls not being in equilibrium should be not more than 4%. The graphite-carbon dioxide dosimeters are 1.9 in. long and have an ionizable volume of 0.176 cm^3. The 0.064-in. diameter aluminum-graphite electrode structure shown in Fig. 3 gives the electrode stability and helps tailor the energy response while limiting the amount of aluminum in the ionizable volume.

2.2 POLYETHYLENE-ETHYLENE THIMBLE IONIZATION CHAMBERS

Nine polyethylene walled ethylene-filled chambers were used. They are sensitive to energy deposition from both gamma rays and fast neutrons. Physically they were 1.85 in. long with an ionizable volume of 0.040 cm^3 as shown in Fig. 4. The aluminum electrode is 0.025 in. in diameter. The diameter of these chambers was also limited to 0.490 in. for the same reasons as the graphite wall dosimeters, resulting in a wall thickness of the polyethylene of 0.385 gm/cm^2. This thickness exceeds the range of 1.0 MeV electrons, providing an equilibrium thickness for 1.25 MeV gamma rays. The polyethylene-walled ionization chambers were placed mainly in poison tubes and therefore, for most of the measurements, were surrounded by water. Since the absorbed dose in water and polyethylene varies by only about 3% in the Compton region, this

increases the effective thickness of the wall material surrounding the ionizable volume, reducing the maximum error caused by the walls not being infinite to about 3%.

III. ABSOLUTE CALIBRATION OF THE ENERGY DEPOSITION IN THE GRAPHITE CHAMBERS

The graphite-walled carbon dioxide-filled thimble ionization chambers were absolutely calibrated by comparison with a Victoreen Model 70-5 thimble chamber.

A 7 MeV beam of electrons from the General Atomic linear accelerator impinged upon a thick fansteel (89% tungsten, 7% nickel, 4% copper) target, producing a bremsstrahlung spectrum with nearly a fission source distribution. Since the electron beam was 7 MeV, which is below the threshold for (γ, n) reactions, no neutrons were produced. A 4-in. thick, 12-in. diameter graphite disc, shown in Fig. 6, was placed 74 in. from and on the center line with the bremsstrahlung target. Eighteen 1/2-in. diameter holes 2-3/4 in. deep were drilled into the disc on a 9-in. diameter circle. One of these holes was enlarged to accomodate the Victoreen chamber. The thickness of graphite between the ionization chamber and the front surface of the disc was 3.2 cm, being slightly greater than the range of a 7 MeV electron. During the measurements, the disc was rotated at 2 rpm to insure a uniform dose to each of the dosimeters. All of the graphite dosimeters were placed in the graphite disc at the same time, eliminating any intercalibration errors among the dosimeters.

Since the range of the Victoreen dosimeter was limited to 25 roentgens, a photodiode-plastic fluor detector[5] was used to monitor the measurements and perform an intercalibration. All of the Landsverk carbon-walled dosimeters were intercalibrated on a relative basis during a single measurement. The instantaneous dose rate was 1×10^3 r/sec,

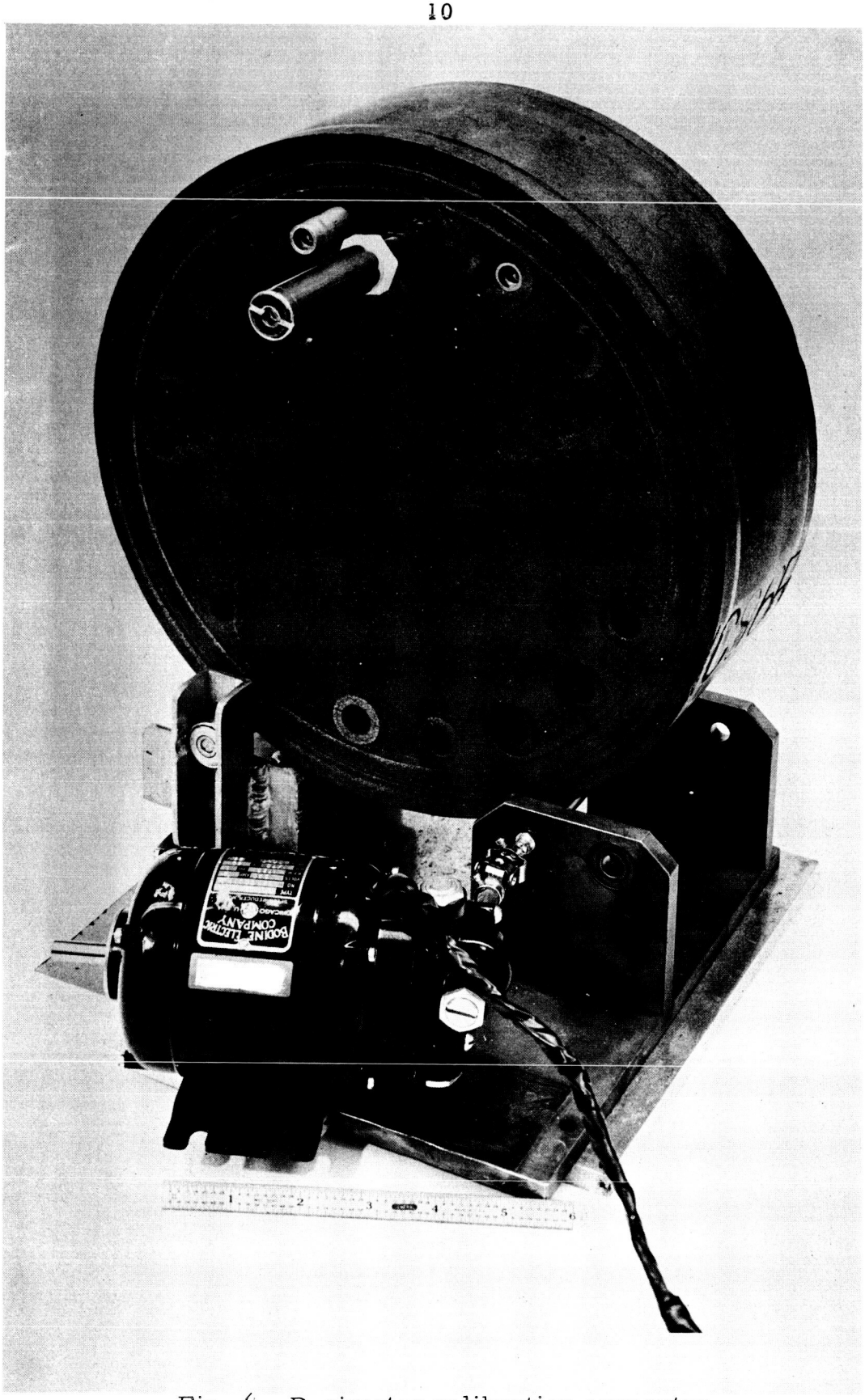


Fig. 6--Dosimeter calibration apparatus

using a pulse length of 4.5 μsec and a pulse repetition rate of 180 per sec from the Linac, yielding a total dose of approximately half scale or about 1400 roentgens for a running time of 30 minutes. The Victoreen chamber has a linear response at dose rates below 5×10^4 r/sec;[5] it is expected that the Landsverk dosimeters are linear up to at least 3×10^3 r/sec.

The exposure level of the Victoreen thimble chamber versus the monitor reading was measured several times to obtain an average value; the maximum deviation was less than 1%. The same geometry used for the Landsverk dosimeters was used for this measurement. For each measurement the Victoreen dosimeter was irradiated for a length of time sufficient to obtain a midscale reading.

The Victoreen ionization chamber reading was corrected by the ratio of the monitor readings for the two measurements and converted to rads by the conversion factor 1 roentgen equals 0.87 rad. The percent of full scale for the Landsverk carbon wall dosimeters was multiplied by 2500 rads, which was the expected full scale reading, and divided by the corrected value of the Victoreen ionization chamber reading in rads to give the sensitivity of the Landsverk dosimeters. The Landsverk chamber reading divided by the sensitivity was used to give the true absorbed dose. It is estimated that this absolute calibration procedure gives the true absorbed dose within ± 5%. The possible individual errors in this calibration are summarized below:

± 2% in the average energy to produce an ion pair in air for the roentgen-to-rad conversion.

± 2% in the reading of the Landsverk dosimeters

± 2% in the reading of the Victoreen dosimeter

± 1% in the value used to convert the Victoreen ionization chamber reading to the intercalibration run for the Landsverk ionization chambers.

± 2% in the monitor readings

± 2% in the true roentgen value of the Victoreen dosimeter.

In this calibration, the Victoreen ionization chamber behaves as a thin-walled ionization chamber filled with air and surrounded by an air equivalent material, in this case carbon. The mass energy absorption coefficient for carbon and air is the same for electron energies from 7 MeV to about 150 keV. The Victoreen dosimeter has a nylon wall with a nominal thickness of 67 mg/cm^2 which is larger than the range of a 270 keV electron. It is intended for use over an effective energy range of 30-400 keV. In the energy range of 30 to 400 keV the chamber had an efficiency of 1.00. However, even at 20 keV its efficiency drops only to 0.90 and at 10 keV it is about 0.65. Therefore, the Victoreen ionization chamber, when used in the thick carbon block, behaves as an air-equivalent dosimeter under the conditions discussed above from about 7 MeV to about 20 keV.

The results of the absolute calibration of the graphite walled carbon dioxide-filled Landsverk dosimeter are tabulated in Table 1. A typical energy response curve for a carbon chamber is shown in Fig. 7 and for a polyethylene chamber in Fig. 8. The energy response for each dosimeter is listed in Table 2 as measured by the Landsverk Electrometer Company.

The polyethylene chambers were also placed in the graphite disc as a means of intercalibration. Since the walls of these chambers are polyethylene the absorbed dose is characteristic of polyethylene and therefore roughly 1.14 larger than the dose in carbon. On this basis an estimate of the rad value of the polyethylene chambers can be made; it is shown in Table 1.

Table 1

DOSIMETER CALIBRATION USING 7.0 MeV BREMSSTRAHLUNG RADIATION

Landsverk Dosimeter Number	Dosimeter Reading in % of Full Scale			Rad Value Obtained from Victoreen R Meter	Corrected Dosimeter Full Scale Rad Value	
	Uncorrected Reading	Drift Correction	Corrected Reading		Indiv. Run	Average
C-1	56.4	0	56.4	2300	4078	4039
C-1	51.0	0	51.0	2030	3960	
C-2	63.5	0	63.5	2300	3622	3622
C-3	63.5	0	63.5	2300	3622	3573
C-3	57.6	0	57.6	2030	3524	
C-1A	63.2	0	63.2	2300	3639	3639
C-5	57.9	0	57.9	2300	3972	3941
C-5	51.9	0	51.9	2030	3911	
C-6	56.0	0	56.0	2300	4107	4107
C-7	58.0	0	58.0	2300	3966	3928
C-7	52.2	0	52.2	2030	3889	
C-8	63.2	0	63.2	2300	3639	3639
C-9	56.8	0	56.8	2300	4049	4038
C-9	50.4	0	50.4	2030	4028	
C-10	61.4	0	61.4	2300	3746	3746
C-11	56.2	0	56.2	2300	4093	4089
C-11	49.7	0	49.7	2030	4085	
C-12	60.9	0	60.9	2300	3777	3777
C-13	71.5	0	71.5	2300	3217	3194
C-13	64.0	0	64.0	2030	3171	
C-14	58.9	0	58.9	2300	3905	3886
C-14	52.5	0	52.5	2030	3866	
C-15	61.8	3.7	58.1	2300	3959	3959
C-16	65.2	.6	64.6	2300	3560	3560
P-1	26.9	0	26.9	2630	9780	9530
P-1	25.0	0	25.0	2320	9280	
P-2	22.2	0	22.2	2320	10440	10440
P-3	22.3	0	22.3	2320	10400	10400
P-4	23.6	0	23.6	2320	9840	9840
P-5	22.0	0	22.0	2320	19530	10530
P-6	25.5	0	25.5	2320	9100	9100
P-7	26.8	0	26.8	2320	8650	8650
P-8	28.0	0	28.0	2320	8280	8280
P-9	22.0	0	22.0	2320	10530	10530

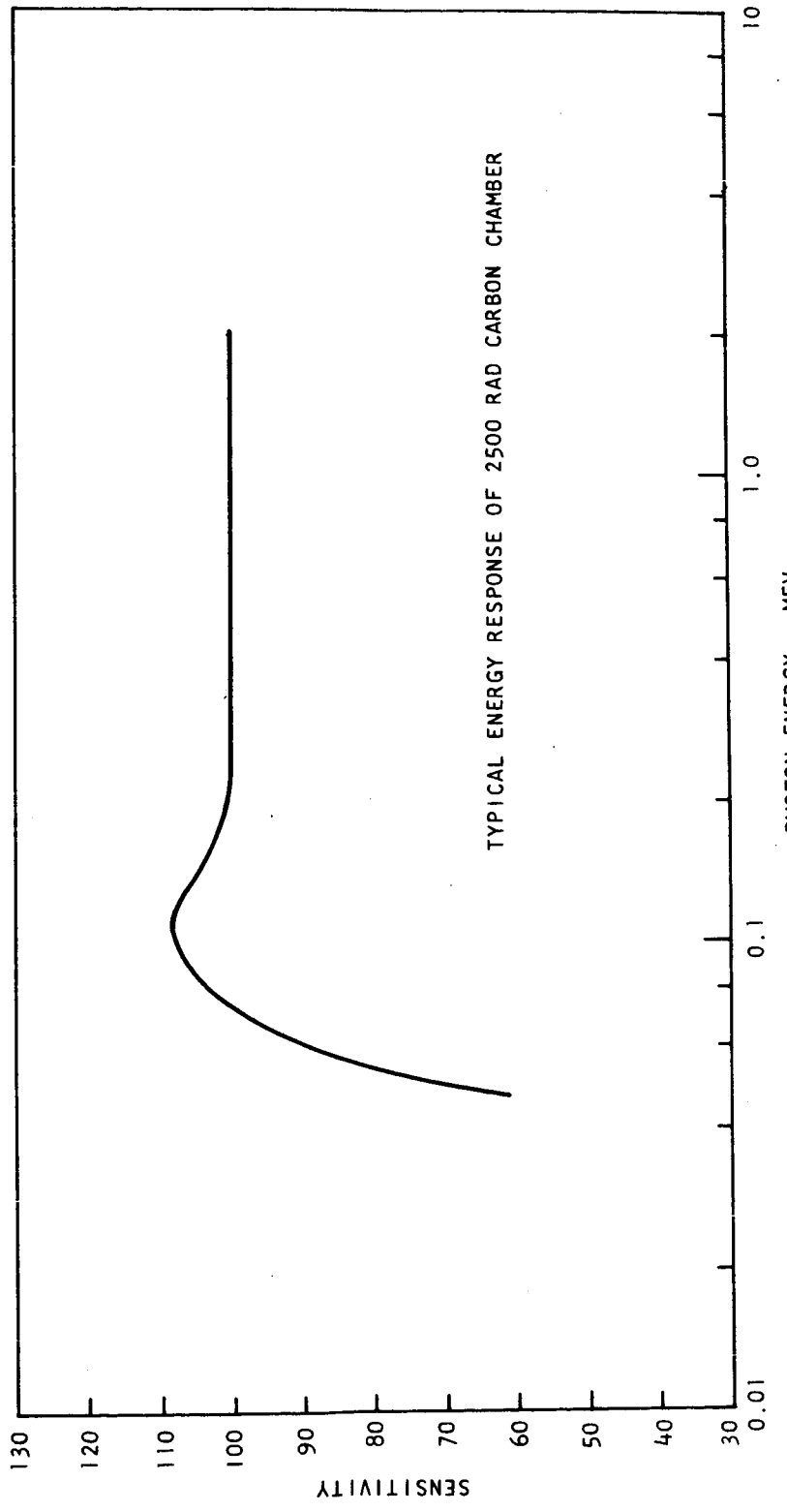


Fig. 7--Typical carbon dosimeter response curve

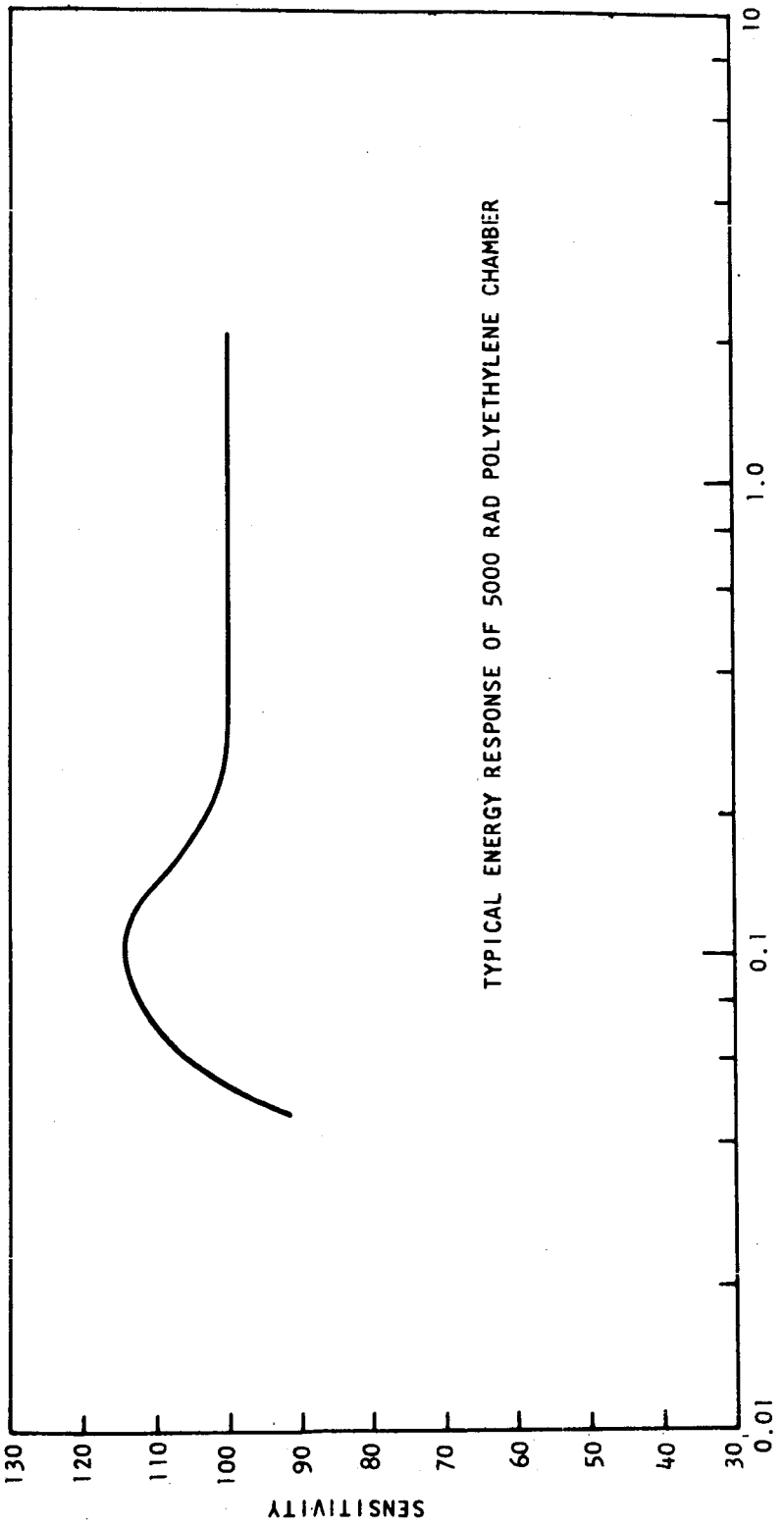


Fig. 8--Typical polyethylene dosimeter response curve

Table 2

THE LANDSVERK ELECTROMETER COMPANY
CALIBRATION CERTIFICATE*

Serial No.	Range	CO^{60}	120 keV	80 keV	46 keV
C1	2500 RAD (Carbon)	76.2	81.1	89.6	46.6
C2	"	78.4	82.5	90.3	44.3
C3	"	94.4	93.5	88.8	51.2
C4	"	74.0	73.3	66.9	35.9
C5	"	86.0	84.8	89.6	43.7
C6	"	84.4	83.6	77.7	42.9
C7	"	87.0	86.0	81.6	46.0
C8	"	84.8	84.2	76.8	42.0
C9	"	80.0	79.4	82.7	40.0
C10	"	90.2	89.3	81.9	43.5
C11	"	85.6	84.8	80.3	41.7
C12	"	85.2	84.4	77.3	41.7
C13	"	107.2	106.2	96.0	49.2
C14	"	85.8	85.0	81.4	43.2
C15	"	84.4	83.4	75.5	42.4
C16	"	94.0	93.1	85.4	44.3
P1	5000 RAD (Polyethylene)	88.6	93.9	90.6	51.8
P2	"	78.0	83.2	81.5	46.8
P3	"	81.2	82.3	78.6	45.4
P4	"	94.4	192.9	103.8	60.9
P5	"	80.0	85.3	84.4	49.4
P6	"	75.2	72.9	69.2	36.1
P7	"	89.8	102.9	86.9	47.9
P8	"	84.6	86.5	85.2	43.2
P9	"	80.9	85.3	86.6	46.5

*Dated November, 1965

IV. ABSOLUTE CALIBRATION OF THE ENERGY DEPOSITION IN THE POLYETHYLENE CHAMBERS

4.1 DESIGN CONSIDERATIONS OF THE CALORIMETER

A calorimeter was designed and built to provide a means of calibration for the polyethylene dosimeters. Water was used for the neutron energy absorbing medium of the calorimeter. Because radiation fluxes produced in the NUROC core when it is operated around 100 watts are insufficient to produce an appreciable temperature rise in water ($\sim 10^{-4}$°C/min at 100 watts could be expected), the calorimeter was designed to be used in the Torrey Pines TRIGA Mark I reactor which may be operated at a much higher power and hence produce a much greater temperature rise rate. The outer jacket of the calorimeter was held to a maximum diameter of 1.250 in. to allow it to fit into a tube in the TRIGA core. Since the size was restricted, an adiabatic jacket was used to reduce heat transfer between the water absorbing mass and its environment. This adiabatic jacket was placed half-way between the outer jacket and the water mass and was made of aluminum and epoxy with a nichrome heating coil potted into the epoxy; adjustment of the power dissipated in the coil almost completely eliminated heat transfer between the water mass and its environment. Heat transfer was further reduced by using fine (.006 in. diameter) copper connection wires to lead into the water mass, keeping all heat paths between the water mass and the adiabatic jacket long and of small cross sectional area. All interior surfaces were painted white and the area around the jacket was evacuated. Since the neutron and gamma energy would be absorbed by the vessel walls as well as by the water, the vessel was designed to have a small mass compared to the water mass. Sheet polyvinyl chloride (PVC) was thermoformed into a two-piece bottle with approximately .004 in. thick walls. A thin ($\sim$.002 in.) coating of epoxy was painted on the outside of the

vessel to eliminate vapor pumping since the PVC is not impervious to water vapor. Details of the calorimeter are shown in Figs. 9,, 10,, and 11.

Fine control of the temperature difference between the water mass and the adiabatic jacket and the ability to accurately sense small incremental temperature changes in the water mass dictated the use of thermistors as temperature sensing elements. The thermistors selected were Fenwall bead, type GA 45J1, with a nominal resistance at 25°C of 50,000 ohms, a spherical diameter of .043 in. and a temperature coefficient of resistance of 4.6%/°C. A pair of these thermistors, matched to within 0.2% of each other, were imbedded, one in the adiabatic jacket and one in the water mass; they form two legs of a bridge circuit as shown in Fig. 11 and were used to control the temperature of the adiabatic jacket with respect to the water mass to eliminate heat transfer. An additional thermistor in the water mass formed one leg of the other bridge circuit of Fig. 11 and was carefully calibrated to allow accurate monitoring of the rate of temperature rise in the water mass. The calibration procedure for the thermistor was as follows: The entire water mass assembly was placed in a large volume of water contained by a vacuum-jacketed glass-walled flask. A copper-constantan thermocouple was located on the surface of the calorimeter water mass and, using an ice bath cold junction, connected to a Rubicon precision potentiometer which allowed accurate determination of the temperature of the water bath. A battery-driven resistance heater was used to slowly raise the temperature of the water bath and the calorimeter water mass assembly suspended within it. The output of the bridge circuit as a function of temperature change was monitored by the Hewlett-Packard 425A microvoltmeter and a Varian strip chart recorder, and was found to be 14.85 millivolts per degree centigrade which agreed very well with calculations based on the manufacturer's rated temperature coefficient of resistance.

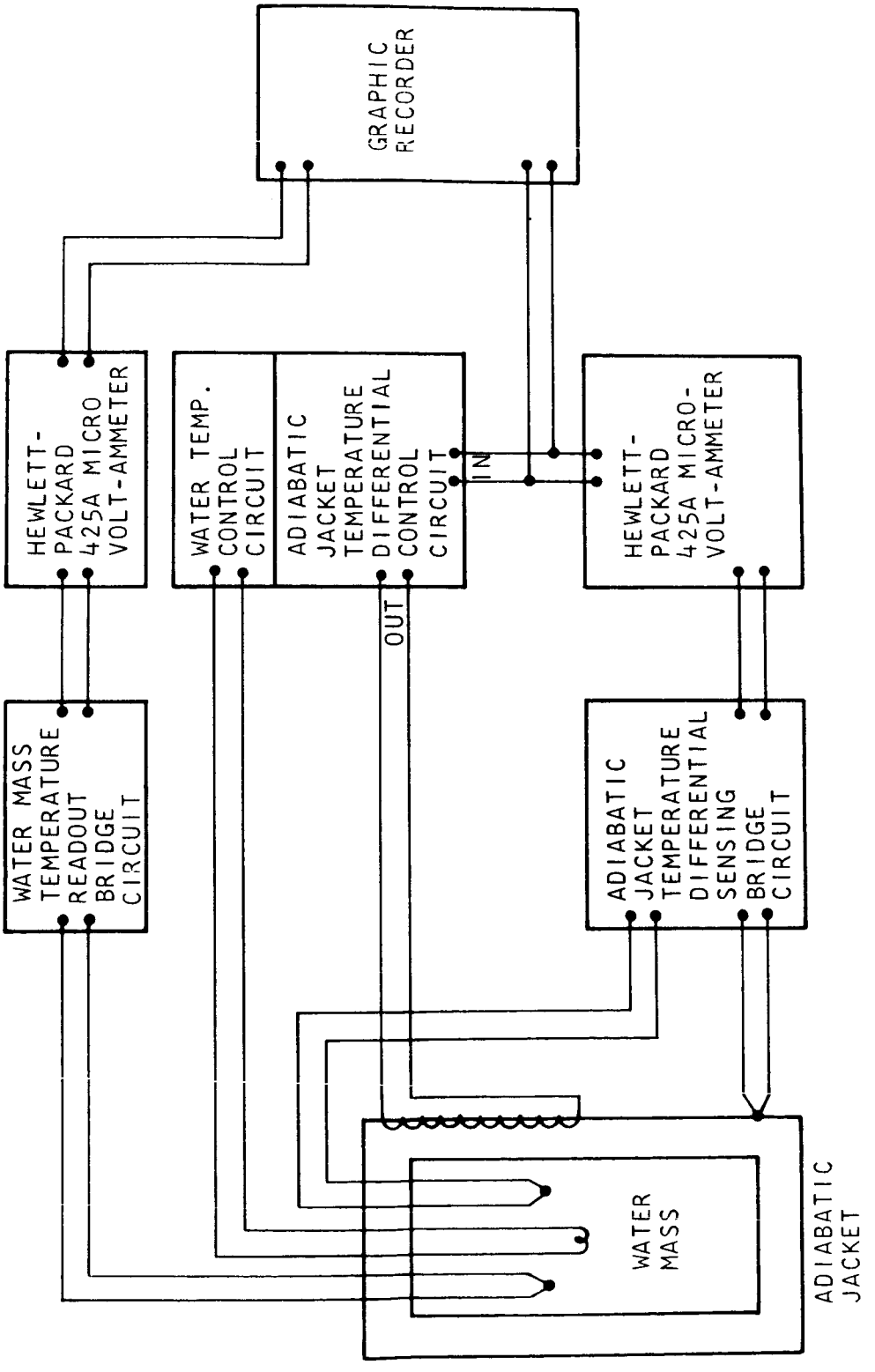


Fig. 9--Calorimeter electronics block diagram

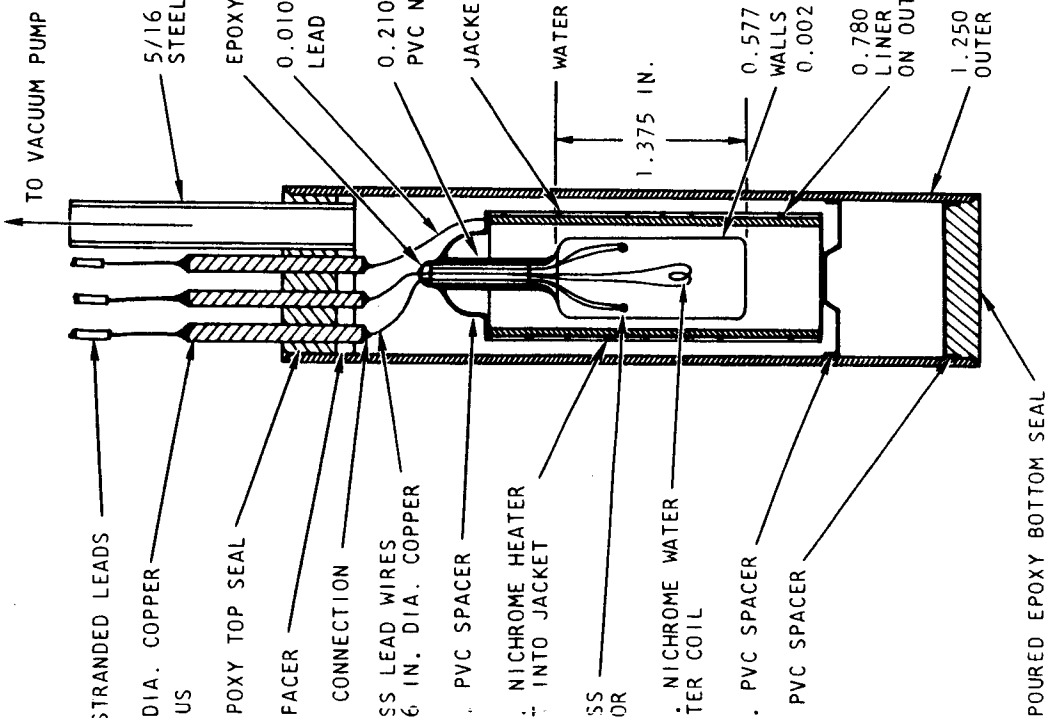


Fig. 10--Cross section of calorimeter

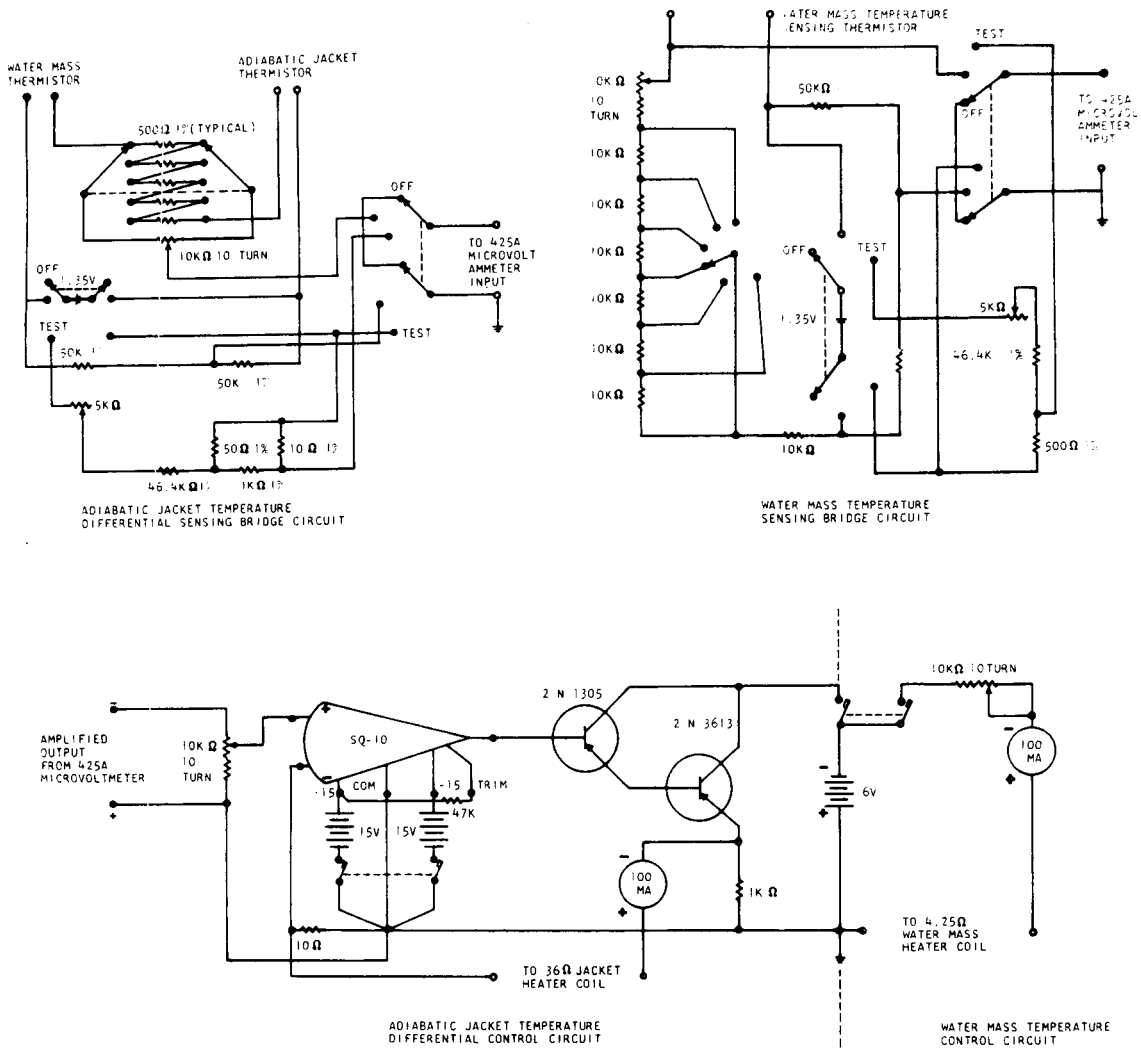


Fig. 11--Calorimeter control and readout circuits

This constant was used in the analysis of subsequent data. A 4.25-ohm nichrome heater coil was included in the water absorbing mass to control the temperature and provide a check on the operation of the system.

4.2 CALORIMETER OPERATION

Once the jacket controls were correctly adjusted, the calorimeter was tested by applying power to the water mass coil and observing the rate of temperature rise of the water mass on the strip-chart recorder. The slope of the temperature rise curve (in millivolts per minute) gives the heating rate since the thermistor constant is known to be 14.85 millivolts per degree centigrade.

When the calorimeter was operated in the reactor, a temperature rise rate of 0.0829°C per minute was observed at a steady state reactor power level of 10 kilowatts; this rate was obtained from the recorder trace which showed a voltage change rate (due to the change in resistance in the calibrated thermistor in the water mass) of 1.23 millivolts per minute. Since 0.0829°C/minute corresponds to 0.0829 gram-calories per gram per minute for water at 13°C (the temperature of the reactor water during the calibration runs) the heat input rate to the calorimeter water mass is given by

$$0.0829 \text{ gram-calories/gram-minute} \times 4.19 \times 10^{7} \text{ ergs/gram-calorie} = 3.47 \times 10^{6} \text{ ergs/gram-minute}$$

and the dose rate in water is

$$\frac{3.47 \times 10^{6} \text{ ergs/gram-minute}}{10^{2} \text{ ergs/gram-rad}} = 3.47 \times 10^{4} \text{ rads/minute at 10 KW}$$

The reactor power level during the irradiation of the dosimeters was 1.8 kilowatts; therefore the dose rate in water corresponding to the readings of the dosimeters is 6250 rads/minute.

As a check on the calorimeter operation, the reactor was operated at 20 kilowatts with a heating rate of .167°C/min being obtained in the calorimeter water mass. Doubling the power doubles the heating rate which indicates that the relative power rates of the reactor are well known and that the calorimeter is able to accurately follow the reactor power level changes.

The results of the absolute calibration of the polyethylene chambers against a water calorimeter is shown in Table 3. Also shown is the calibrated rad reading of several carbon ion chambers which were placed in the same reactor core position as the polyethylene chambers.

V. THIMBLE IONIZATION CHAMBER MEASUREMENTS IN CORE III OF THE TUNGSTEN NUCLEAR ROCKET REACTOR

The Tungsten Nuclear Rocket Reactor core exhibited a twelve-fold symmetry as shown in Fig. 2. All of the thimble ionization chamber measurements were made in one sector of symmetry. The placement of these chambers is shown in Fig. 12. A total of 25 ionization chambers was used for each measurement: 16 graphite and 9 polyethylene walled chambers. A total of four runs was required; the power level for each run was 84.2 watts.

The ionization chambers were placed above and below the zirconium stud in the fuel elements using 3/8-in. diameter, 0.060-in. wall thickness aluminum tube spacers. In the poison tubes, 5/16-in. diameter, 0.060-in. wall thickness aluminum tube spacers were used and the void between chambers was filled with cadmium nitrate. For each run the same graphite-walled chamber was placed in the G-7 fuel element and the same polyethylene chamber in the G-16 poison tube to monitor

Table 3a

CALIBRATION OF THE ION CHAMBERS IN THE TRIGA REACTOR

Landsverk Dosimeter Number	Dosimeter Reading in Percent of Full Scale			Rad Value Obtained from Calorimeter	Corrected Dosimeter Full Scale Rad Value	
	Uncorrected Reading	Position Correction	Corrected Reading		Individual Run	Average
P-1	9.5	.982	48.6	6250	12860	12860
P-2	41.1	1.02	41.9	6250	14920	14920
P-3	43.4	1.02	44.3	6250	14090	14090
P-4	45.0	.982	44.1	6250	14190	14190
P-5	43.1	1.02	43.9	6250	14220	14220
P-6	55.4	.982	54.4	6250	11480	11400
P-6	56.3	.982	55.3	6250	11310	
P-7	50.4	1.02	51.4	6250	12150	12150
P-8	51.5	.982	50.6	6250	12360	12360
P-9	43.5	.982	42.7	6250	14620	14620
P-9	41.3	1.02	42.2	6250	14810	
P-9	42.4	1.02	43.3	6250	14420	

Table 3b

Landsverk Dosimeter Number	Dosimeter Reading in Percent of Full Scale			Rad Value for Dosimeter Reading Corresponding to Percent Full Scale
	Uncorrected Reading	Position Correction	Corrected Reading	
C-2	60.8	1.02	62.0	2246
C-5	57.4	1.02	58.6	2309
C-9	53.3	1.02	54.3	2152
C-14	56.5	.982	55.5	2196

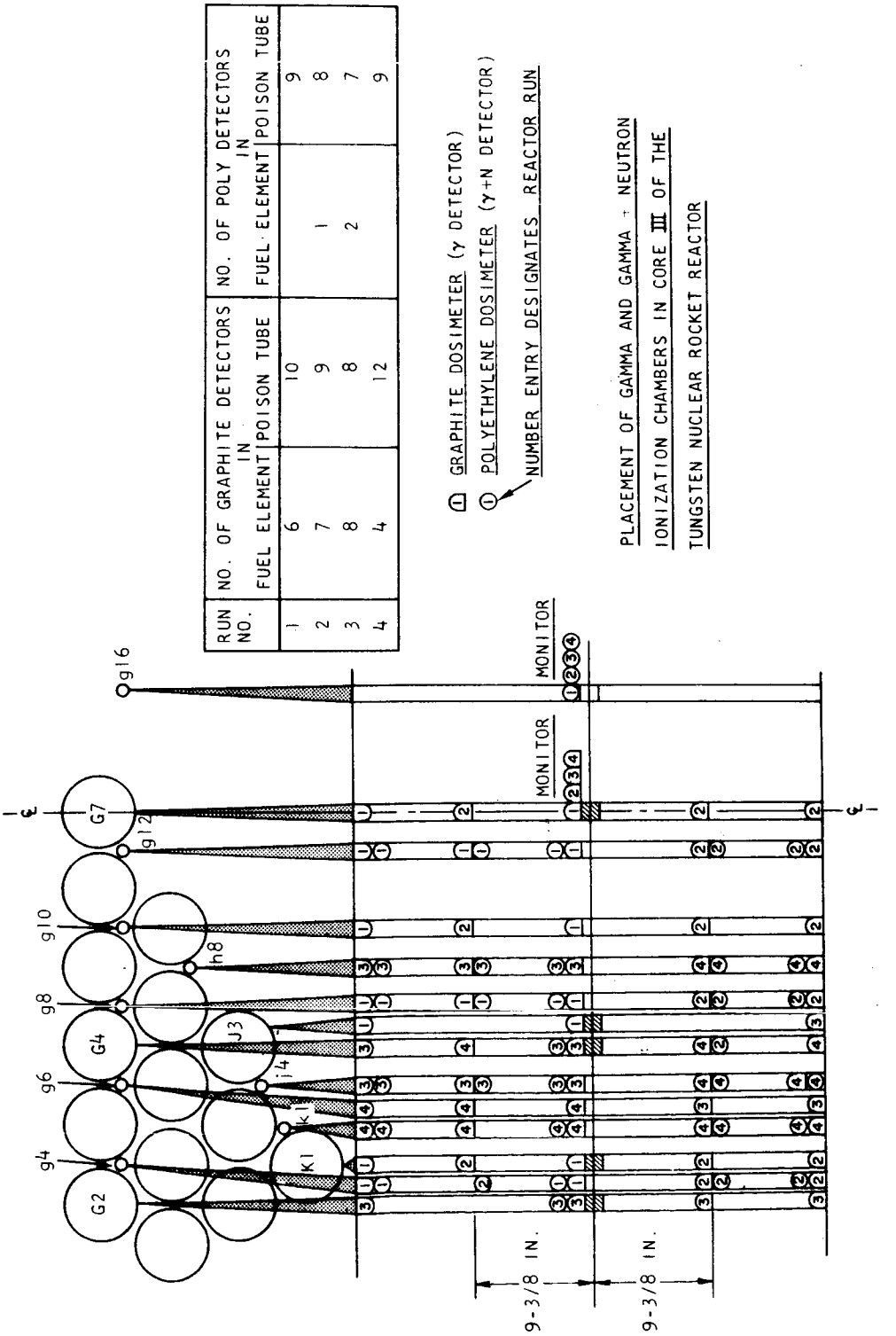


Fig. 12--Placement of dosimeters in Core III of the tungsten nuclear rocket reactor

the relative power level between runs. The relative variation in the power level from run to run as indicated by the ionization chambers was about 3%. Each run lasted 40 minutes; the period of the reactor was 30 seconds, resulting in a total of about 139 seconds to reach full power (about 6% of the total running time). It took approximately 8 minutes to remove the chambers from the poison tubes and about 10 minutes to remove them from the fuel elements after the reactor was shut down.

VI. TIME HISTORY OF THE GAMMA INTENSITY IN CORE III OF THE TUNGSTEN NUCLEAR ROCKET REACTOR

A determination of the gamma intensity time history was made for each of the four reactor operating runs in which dosimetry measurements were made. A gamma scintillation detector capable of discriminating against fast neutrons was used. The recorded output of this detector provided a measurement of the relative gamma intensity from the reactor core as a function of time. The contribution of delayed gammas to the prompt radiation is illustrated in Figs. 13 to 16.

The scintillating solution used in the gamma detector employed the nonhydrogeneous hexafluorobenzene (C_6F_6) as a solvent[6] in order to discriminate against fast neutrons. Small concentrations of two hydrogeneous scintillators were used in solution; para-terphenyl at 4 grams per liter and dimethyl POPOP at one gram per liter. The binary solution was sealed in a ten-milliliter pyrex flask in an argon atmosphere to prevent oxygen quenching of the scintillations which were observed by a DuMont 6292 photomultiplier tube. The output current from the photomultiplier varied between 1.5×10^{-8} ampere and 4.5×10^{-7} ampere and was recorded on a graphic recorder.

The detector was positioned about two feet above the beryllium reflector at the edge of the core. The relative intensity of the gamma radiation was measured as a function of time for each of the four reactor

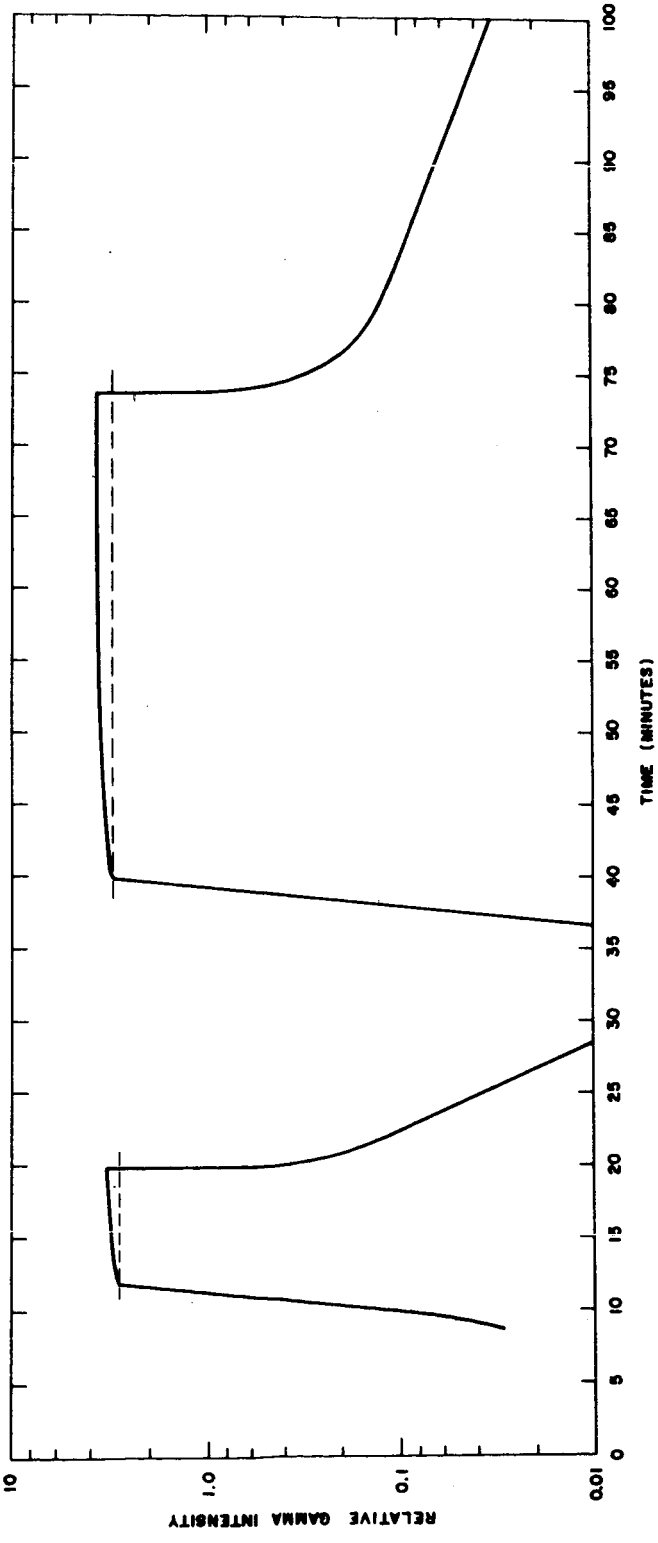


Fig. 13--Gamma intensity time history for dosimeter run one

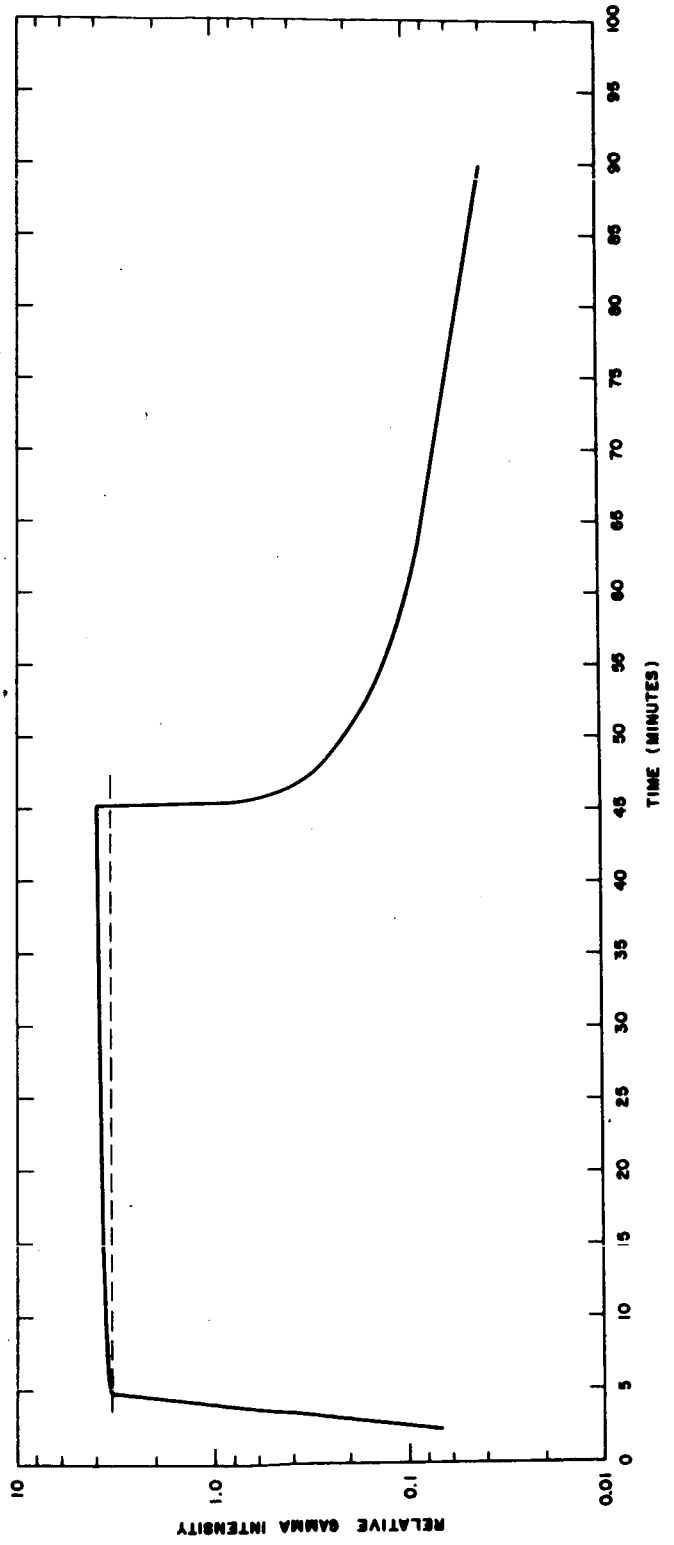


Fig. 14--Gamma intensity time history for dosimeter run two

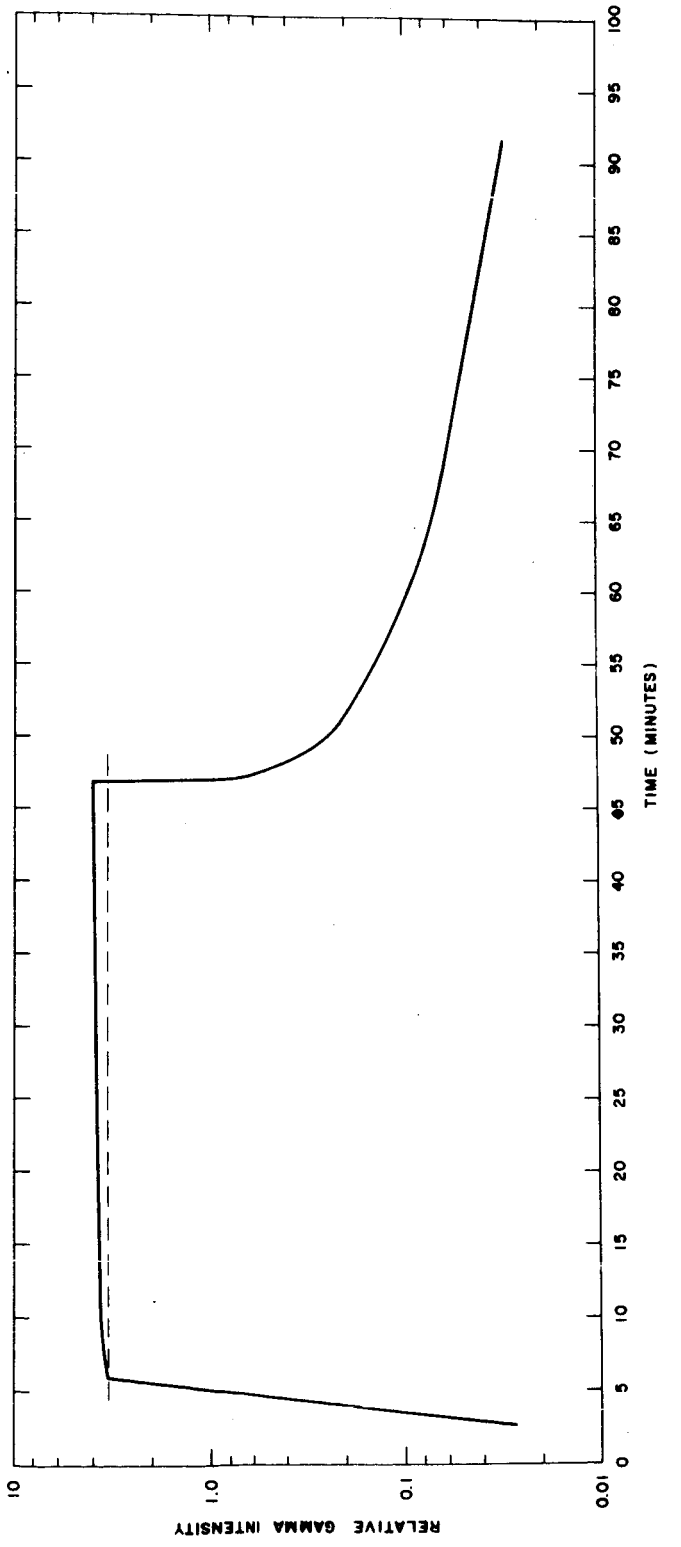


Fig. 15--Gamma intensity time history for dosimeter run three

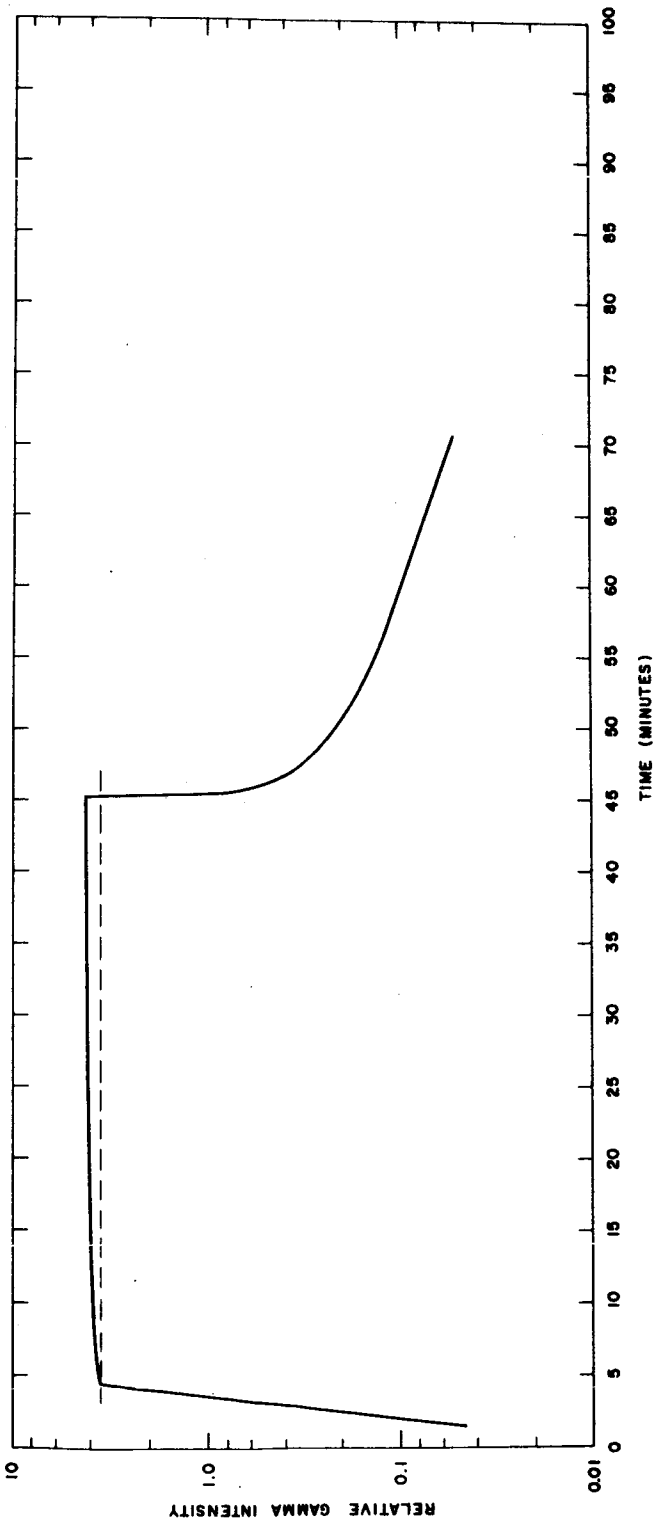


Fig. 16--Gamma intensity time history for dosimeter run four

operating runs in which the gamma and neutron fluxes were mapped using the carbon and polyethylene ion chambers.

The relative gamma intensity as a function of time for runs 1 through 4 is illustrated in Figs. 13 through 16 respectively. Typical of each curve is the exponential increase in intensity on the 30-second period of the reactor as it is brought up to power, leveling off at a constant value of 84.2 watts. Each run was continuous for approximately 40 minutes with the exception of run 1 in which a scram occurred during the run.

These graphs have been corrected for background effects, including residual nuclear radiation and detector dark current. An examination of each of the curves confirms the expected buildup in intensity of delayed gammas from fission during the run and the gradual decay after shutdown. For runs 2, 3, and 4 the intensity of delayed gamma radiation just prior to shutdown of the reactor is 19.7%, 18.9%, and 19.0% respectively, of the prompt gamma intensity. These numbers correspond very well with the point on the intensity curve where the exponential decay begins at reactor shutdown. The decay tail of delayed gammas is clearly a composite of several decay modes: the longest mode measured here, using the data for runs 2 and 3, corresponds to a half-life of approximately 40 minutes.

VII. RESULTS AND DISCUSSIONS OF SOURCES OF ERROR IN THE ABSORBED DOSE MEASUREMENTS IN CORE III OF THE TUNGSTEN NUCLEAR ROCKET REACTOR

The results of the axial measurements of the gamma and neutron absorbed doses in Core III of the Tungsten Nuclear Rocket Reactor are graphed in Figs. 17, 18, 19, and 20 and tabulated in Table 4. The lines are the "best fit" to the data. The arrows on the graphs indicate possible defective data. The C-15 carbon dosimeter had an exceptionally high

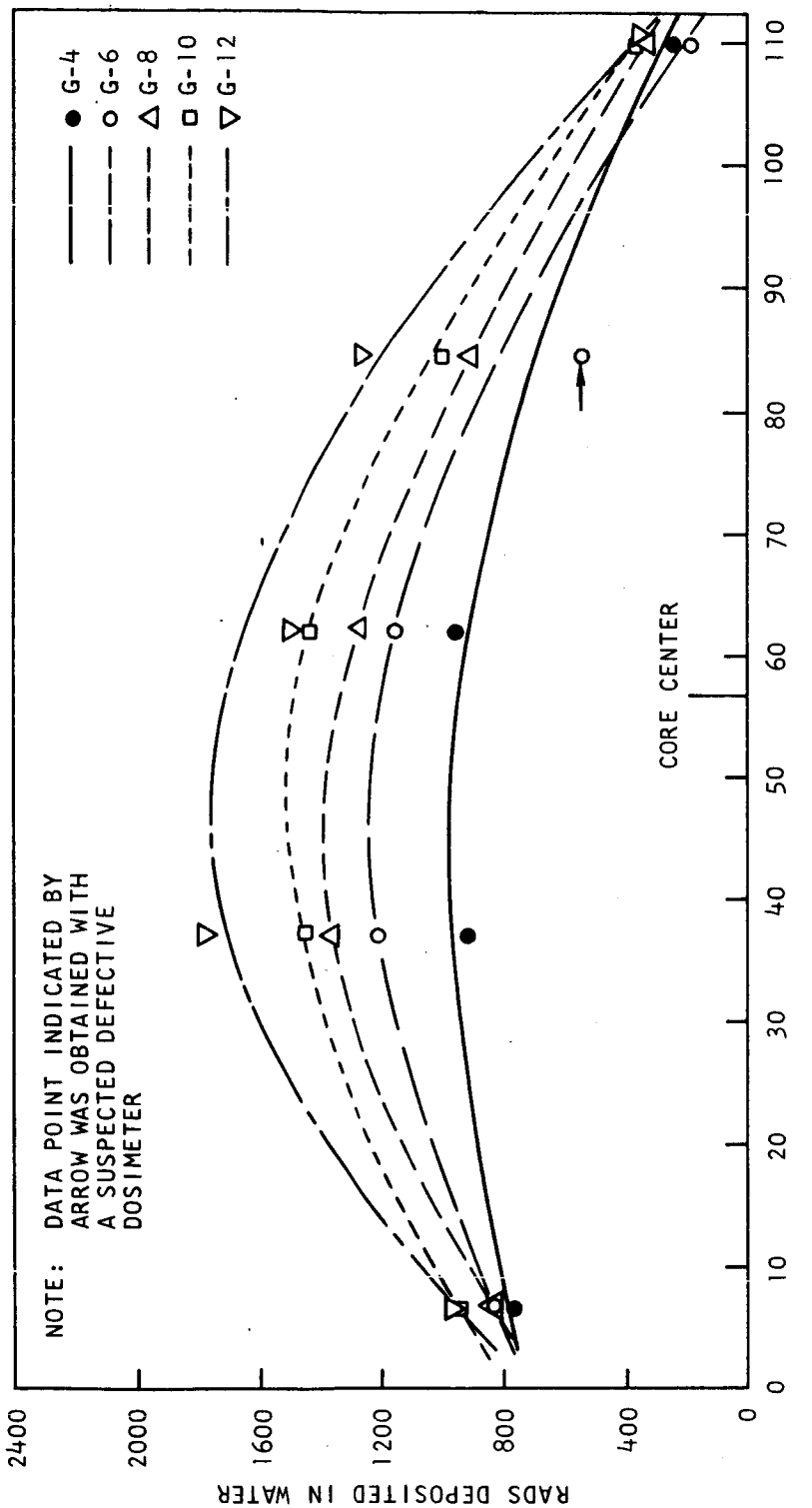


Fig. 17--Absorbed dose in graphite dosimeters in nuclear rocket core poison tubes

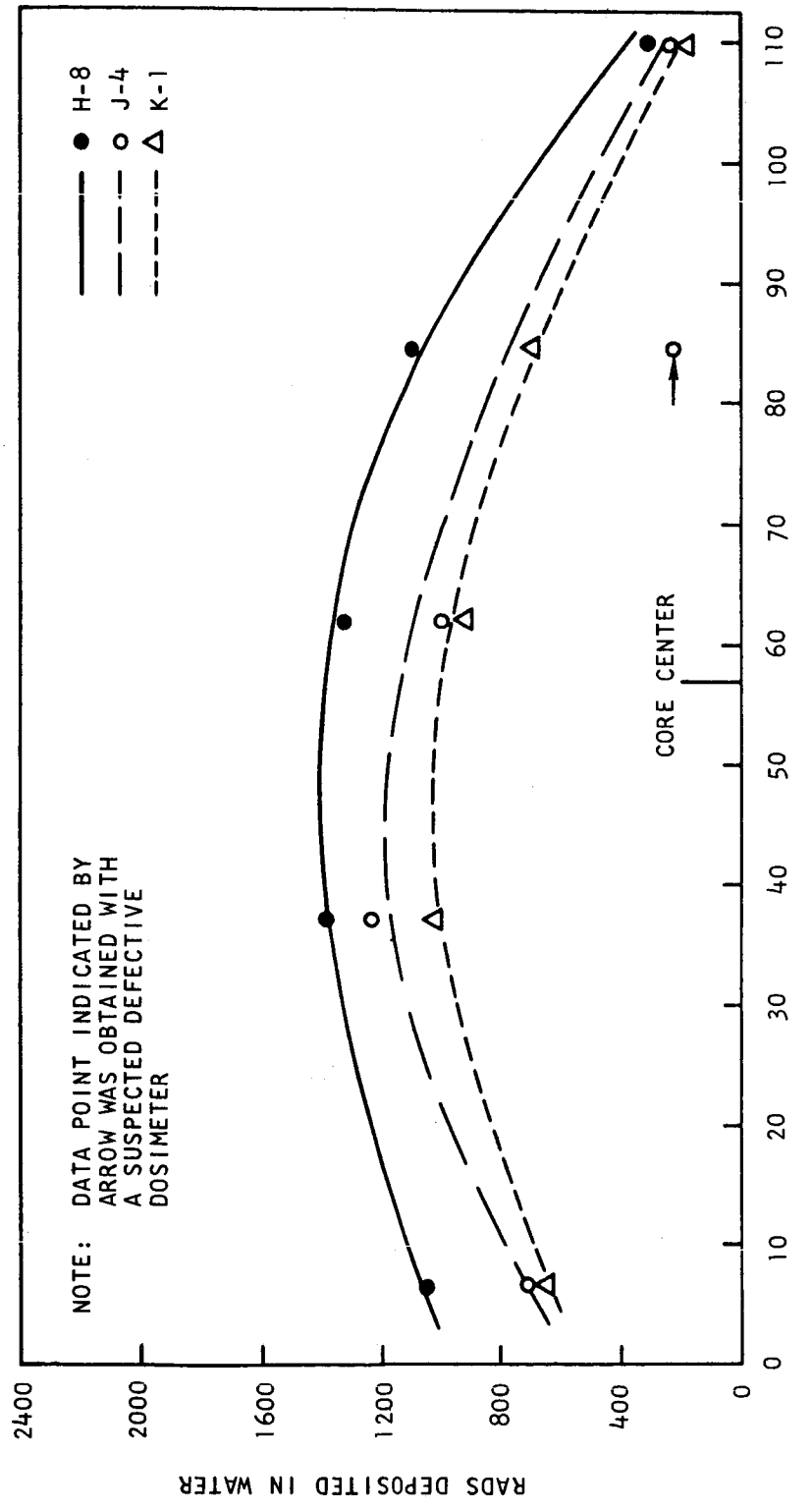


Fig. 18--Absorbed dose in graphite dosimeters in nuclear rocket core poison tubes

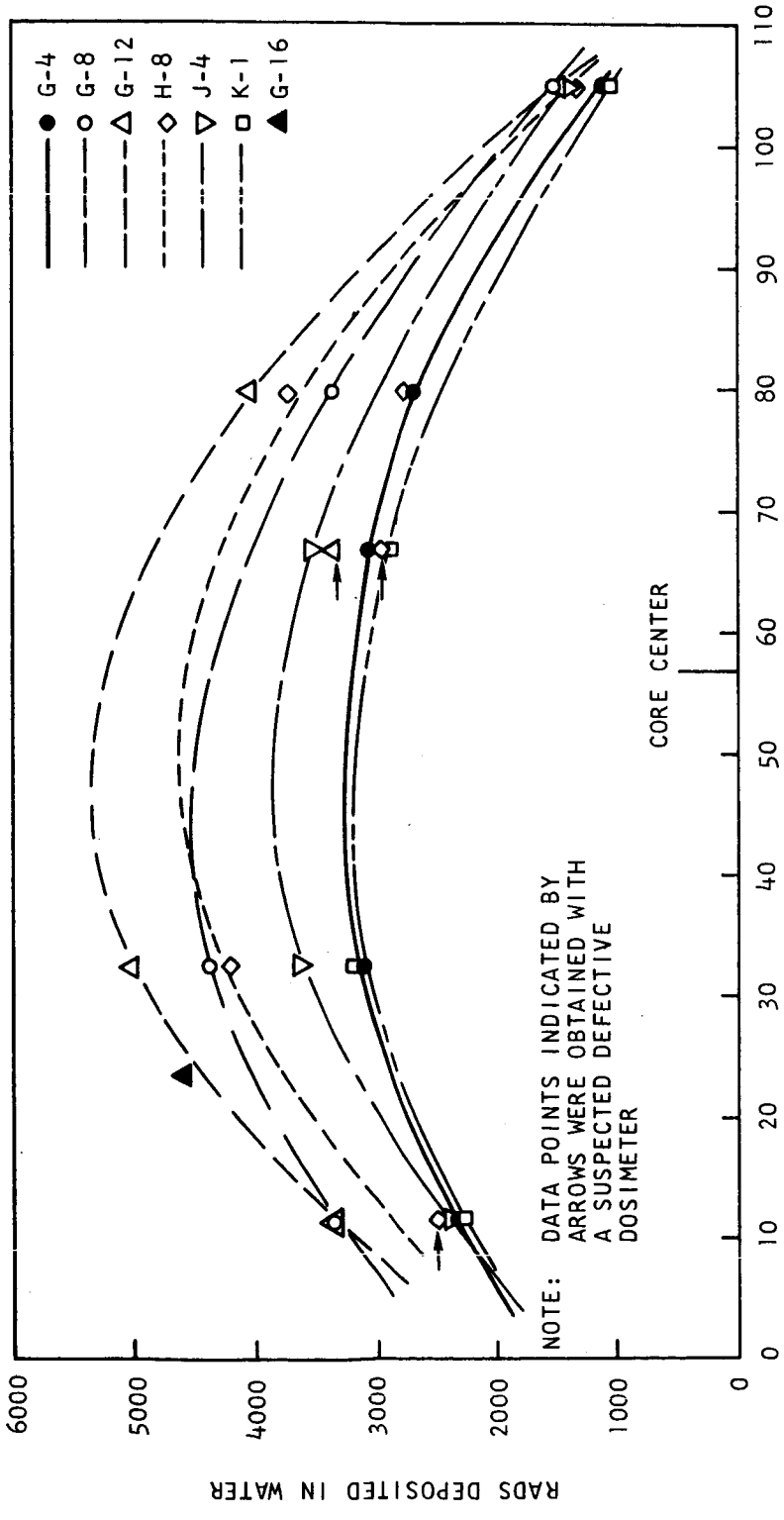


Fig. 12--Absorbed dose in polyethylene dosimeters in nuclear rocket core poison tubes

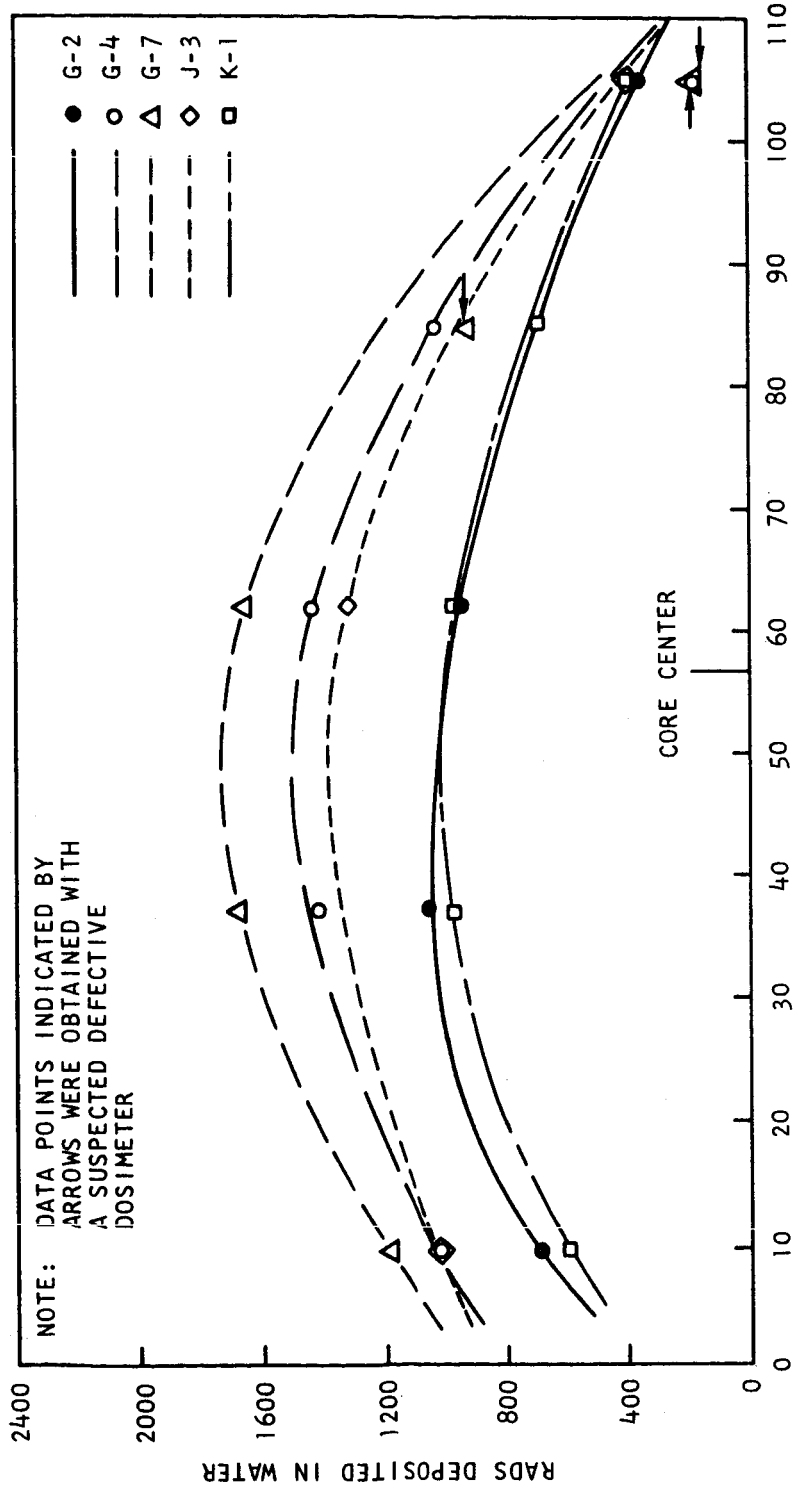


Fig. 20--Absorbed dose in graphite dosimeters in nuclear rocket core fuel elements

Table 4

RESULTS OF IONIZATION CHAMBER MEASUREMENTS IN CORE III OF THE TUNGSTEN NUCLEAR ROCKET REACTOR

Poison Tube or Fuel Element	Distance from Core Bottom Plate Surface to Center of Dosimeter Active Volume, cm	Dosimeter Number C=Graphite P=Polyethylene	Dosimeter Reading in % of Full Scale (Corrected for Drift)	Normalizing Factor to Run 1 using C-14 as a Monitor	Absorbed Dose in Water at Point of Measurement Rads	Absorbed Dose in Carbon Point of Measurement Rads
G-2	9.4	C-16	19.2	1.021		698
G-2	37.1	C-11	24.8	1.021		1035
G-2	62.1	C-1	23.9	1.021		965
G-2	105.1	C-12	9.4	1.021		362
G-2	67.0	P-1	22.8	1.021	2994	
G-4	9.4	C-5	26.0	1.009		1034
G-4	37.1	C-1	34.8	1.009		1418
G-4	62.1	C-6	35.1	1.021		1472
G-4	84.7	C-7	26.2	1.009		1038
G-4	105.1	*C-15	4.8	1.021		194
G-4	32.4	*P-6	28.8	1.026	3368	
G-4	67.0	P-2	29.8	1.021	4540	
G-7	9.4	C-5	30.0	1.026		1213
G-7	37.1	C-12	44.3	1.026		1717
G-7	62.1	C-14 (Run 1	43.1	1.000		1678
G-7	62.1	C-14 (Run 2	42.1	1.026		1678
G-7	62.1	C-14 (Run 3	42.3	1.021		1678
G-7	62.1	C-14 (Run 4	42.8	1.009		1678
G-7	84.7	*C-15	22.9	1.026		930
G-7	105.1	*C-15	5.1	1.000		202
J-3	9.4	C-13	31.7	1.021		1034
J-3	62.1	C-12	35.1	1.000		1326
J-3	105.1	C-16	11.3	1.000		402
K-1	9.4	C-16	16.8	1.026		614
K-1	37.1	C-11	23.8	1.026		998
K-1	62.1	C-11	23.6	1.000		965
K-1	84.7	C-1	17.1	1.026		709
K-1	105.1	C-13	10.6	1.000		339
g-4	6.6	C-3	21.6	1.026		792
g-4	37.1	C-1A	25.3	1.026		945
g-4	62.1	C-1	23.6	1.000		953
g-4	110.0	C-3	6.6	1.000		236
g-4	11.4	P-1	17.8	1.026	2349	
g-4	32.4	P-5	21.6	1.026	3151	
g-4	67.0	P-2	20.6	1.000	3073	
g-4	80.0	P-4	18.3	1.026	2664	
g-4	105.3	P-1	8.6	1.000	1105	

*Suspected defective dosimeter

Table 4 (Continued)

Poison Tube or Fuel Element	Distance from Core Bottom Plate Surface to Center of Dosimeter Active Volume, cm	Dosimeter Number C=Graphite P=Polyethylene	Dosimeter Reading in % of Full Scale (Corrected for Drift)	Normalizing Factor to Run 1 using C-14 as a Monitor	Absorbed Dose in Water at Point of Measurement Rads	Absorbed Dose in Carbon Point of Measurement Rads
g-6	6.6	C-3	23.3	1.021		850
g-6	37.1	C-5	30.8	1.021		1239
g-6	62.1	C-12	30.5	1.009		1162
g-6	84.7	*C-15	13.6	1.009		543
g-6	110.0	C-13	5.6	1.009		180
g-8	6.6	C-2	23.1	1.026		858
g-8	37.1	C-6	33.5	1.026		1412
g-8	62.1	C-2	35.1	1.000		1271
g-8	84.7	C-1A	25.1	1.000		913
g-8	110.0	C-10	8.6	1.000		322
g-8	11.4	P-3	22.3	1.026	3223	
g-8	32.4	P-2	28.6	1.026	4378	
g-8	80.0	P-5	23.6	1.000	3356	
g-8	105.3	P-4	10.6	1.000	1504	
g-10	6.6	C-10	25.3	1.026		972
g-10	37.1	C-7	37.3	1.026		1503
g-10	62.1	C-5	36.6	1.000		1442
g-10	84.7	C-13	31.2	1.026		1022
g-10	109.7	C-6	8.6	1.000		353
g-12	6.6	C-9	23.8	1.026		986
g-12	37.1	C-8	48.5	1.026		1811
g-12	62.1	C-7	38.1	1.000		1497
g-12	84.7	C-8	34.6	1.000		1259
g-12	110.0	C-9	8.6	1.000		347
g-12	11.4	P-7	27.0	1.026	3365	
g-12	32.4	P-8	40.4	1.026	5123	
g-12	67.0	*P-6	29.6	1.000	3374	
g-12	80.0	P-8	32.6	1.000	4029	
g-12	105.3	P-7	12.1	1.000	1470	
h-8	6.6	C-16	29.5	1.009		1059
h-8	37.1	C-10	36.8	1.009		1391
h-8	62.1	C-7	33.5	1.021		1344
h-8	84.7	C-8	29.9	1.021		1111
h-8	110.0	C-9	7.3	1.021		301
h-8	11.4	*P-6	21.3	1.009	2450	
h-8	32.4	P-5	29.3	1.009	4204	
h-8	67.0	*P-6	25.8	1.021	3003	
h-8	80.0	P-8	29.0	1.021	3660	
h-8	105.3	P-7	10.8	1.021	1340	

*Suspected defective dosimeter

Table 4 (Continued)

Poison Tube or Fuel Element	Distance from Core Bottom Plate Surface to Center of Dosimeter Active Volume, cm	Dosimeter Number C=Graphite P=Polyethylene	Dosimeter Reading in % of Full Scale (Corrected for Drift)	Normalizing Factor to Run 1 using C-14 as a Monitor	Absorbed Dose in Water at Point of Measurement Rads	Absorbed Dose in Water at Point of Measurement Rads
j-4	6.6	C-9	17.8	1.009		725
j-4	37.1	C-8	34.0	1.009		1248
j-4	62.1	C-2	27.5	1.021		1017
j-4	84.7	*C-1A	5.9	1.021		219
j-4	110.0	C-10	6.7	1.021		256
j-4	11.4	P-7	19.6	1.009	2403	
j-4	32.4	P-8	29.1	1.009	3629	
j-4	67.0	P-3	24.4	1.021	3510	
j-4	80.0	P-5	18.8	1.021	2730	
j-4	105.3	P-4	9.0	1.021	1304	
k-1	6.6	C-3	18.3	1.009		660
k-1	37.1	C-6	24.8	1.009		1028
k-1	62.1	C-2	25.0	1.009		914
k-1	84.7	C-11	16.9	1.009		697
k-1	110.0	C-1A	5.3	1.009		195
k-1	11.4	P-1	17.6	1.009	2284	
k-1	32.4	P-2	21.1	1.009	3176	
k-1	67.0	P-3	20.3	1.009	2886	
k-1	105.3	P-4	7.3	1.009	1045	
g-16	23.5	P-9	31.1	1.000	4547	
g-16	23.5	P-9	30.8	1.026	4620	
g-16	23.5	P-9	30.3	1.021	4523	
g-16	23.5	P-9	31.3	1.009	4617	

*Suspected defective dosimeter

drift rate for which it was difficult to accurately correct. One reading of the C-1A carbon chamber reading is also suspect due to rough handling. The readings of the P-6 polyethylene dosimeter are suspect because the intercalibration ratio for the 7 MeV bremsstrahlung and the water calorimeter were different.

Two important considerations need to be elucidated. The polyethylene chambers were calibrated against a water calorimeter. This means that the absorbed dose for these chambers is characteristic of water and not polyethylene. Since they were calibrated in the TRIGA Mark I, the degree of accuracy of the calibration of the polyethylene dosimeters depends on the degree of accuracy of the assumption that the gamma and neutron spectra in Core III of the Tungsten Nuclear Rocket Reactor is similar to that in TRIGA Mark I. The carbon dosimeters have been found to have an inherent response to neutrons. This response is difficult to determine precisely but has been estimated to be about 28%, and is also contingent upon the above discussed assumption. The neutron response of the carbon chamber was estimated by placing some of the carbon chambers in the same position as the calorimeter was placed. The ratio of the gamma dose in water to the dose in carbon is $D_{H_2O}/D_C = 1.11$. The ratio of the neutron dose in water to the dose in carbon is $D_{H_2O}/D_C = 7.0$. If the gamma dose in carbon is represented by A and the neutron dose in carbon by B then:

$$\text{Carbon:} \qquad A + B = R_1$$

$$\text{Water:} \qquad 1.11\,A + 7\,B = R_2$$

Where R_1 and R_2 are the rad values obtained for the carbon chamber and the water calorimeter respectively.[7] If these equations are solved simultaneously then the neutron response of the carbon chamber can be determined and is B/R_1. The data have not been corrected for the fast neutron response of the carbon chambers. It should be pointed out that the neutron response of the carbon chambers is a strong function of neutron energy and that additional calculations are required to determine the average response in the core spectrum.

It is estimated that the absolute calibration procedure for the polyethylene chambers gives the true absorbed dose in water within ± 8%.

The possible individual errors in this calibration are summarized below:

± 2% in the reading of the Landsverk dosimeter

± 2% in the relative monitor of the TRIGA power level

± 2% in the uncertainty in time of the insertion of the dosimeters in the TRIGA core.

± 7% in the calibration of the calorimeter

± 1% in the dosimeter position corrective factor.

The possible individual errors in the measurements in Core III of the Tungsten Nuclear Reactor are summarized below:

± 2% in the reading of the Landsverk dosimeter

± 8% in the absolute calibration of the polyethylene chamber

± 5% in the absolute calibration of the carbon dosimeters

± 3% in the time at which the reactor is at maximum power level.

A negligible error was in the dose received by the chambers while being removed from the poison tubes and fuel elements. The fuel elements were reading an average of 2 r/hr at the surface and the dosimeters remained in the fuel elements for a maximum of 15 minutes after the run.

On this basis the probable error in the measurements using the polyethylene chambers is ± 9%; for the carbon dosimeters it is ± 6%.

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